Steady State Performance Investigation of a Three Phase Induction Motor Running Off Unbalanced Supply Voltages

Aslan Sabahaldeen Jalal Abdi

Department of Mechatronics Engineering/ Al-Khwarizmi College of Engineering/ University of Baghdad
Email: aslannabdi@yahoo.com; aslan.kecbu@uobaghdad.edu.iq

Abstract

The objective of this work is to investigate the performance of a conventional three phase induction motor supplied by unbalanced voltages. An effort to study the motor steady state performance under this disturbance is introduced. Using per phase equivalent circuit analysis with the concept of symmetrical components approach, the steady state performance is theoretically calculated. Also, a model for the induction motor with the MATLAB/Simulink SPS tools has been implemented and steady state results were obtained. Both results are compared and show good correlation as well. The simulation model is introduced to support and enhance electrical engineers with a complete understanding for the steady state performance of a fully loaded induction motor operating from unbalanced supply voltages.

Keywords: Three phase induction motor, unbalanced supply voltage, MATLAB/simulink.

1. Introduction

For industrial and mining applications, three phase induction motors (IM) are the prime movers for the vast majority of machines. These motors can be operated either directly from the mains or from variable frequency drives. In modern industrialized countries, more than half of the total electrical energy used in those countries is converted to mechanical energy through AC induction motors.

In the last decade, using three phase squirrel cage AC induction motors (IM) with AC Variable Speed Drives has increasingly become a common practice. Since the 1980's, the popularity of the variable speed drives has grown rapidly, mainly due to advances in power electronics and digital control technology affecting both the cost and performance of this type of speed control. To clearly understand how the variable speed drive system works, it is necessary to understand the principles of operation of this type of motor.

The most popular analytical method that has been used in analyzing the IMs is the equivalent circuit method [1-4]. To understand the performance of an IM operating from unbalanced supply voltages, it is useful to electrically represent the motor by an equivalent circuit [5]. It is worth mentioning that the NEMA standard recommends that the voltage deviation from the motor rated voltage not exceed ±10% at the rated frequency [6].

Computer models and simulation tools have been extensively used to support and enhance electric machinery courses. MATLAB with its toolboxes: Simulink [8] and SimPowerSystems [9] is one of the most popular software packages used to investigate the transient and steady-state characteristics of electric machines [10 – 13].

Ayasun and Nwankpa [14] had presented simulation models of induction motor tests performed to obtain parameters of the per-phase equivalent circuit of three-phase induction motors. The results imply that MATLAB/Simulink is a good simulation tool to model induction motor tests and to evaluate its steady – state characteristics. However, the reported results do not discuss the effect of unbalanced supply voltage on the induction motor steady – state characteristics.

J. D. Kueck, et. al, [15] have reported that current unbalances produced by relatively small voltage unbalances appear to be a serious concern in susceptible motors if they are operated with a small or no service margin. Unbalance can be due to either unbalance in the motor itself or unbalance in the power supply due to unbalance in voltage magnitudes or phase angles or level of harmonic distortion between phases. In their particular case, Impedance measurements at the motor terminals have been carried out. This is determined by measuring the impedance between each of the three winding terminals immediately after the motor was de-energized from continuous operation at room temperature and left to cool to room temperature. These three values are averaged and the maximum deviation from the average is expressed in percent. Measurements over 4 months revealed impedance unbalance growing up with time as it varied from 5.6% up to 8%. Regardless of the source of the unbalance, unbalanced voltages result in negative sequence currents which cause additional motor heating, unbalanced forces, and reduction in speed. The reported results were obtained regarding the effect of unbalanced voltage levels from 0 to ±4%.

In Iraq, with the existing poor power grid, the per phase average unbalanced voltage levels are from 4.6% to 16%, and the voltage is always below the nominal level, as will be explained later. One of the most effective causes of this voltage unbalance is that a combination of single phase and three phase loads on the same distribution system, with the single phase loads unequally distributed.

The first object of this work is to analyze the three phase induction motor supplied by low imbalance voltages using the concepts of symmetrical components and equivalent circuit methods. The second object is to introduce MATLAB/Simulink model representing the steady state operation of three phase induction motor running off unbalanced supply voltages. The reason that MATLAB, with its SPS toolboxes, was selected to model the induction motor is that it is the main software package that has been used by almost all engineers graduated from the author's institution as a computation tool to reinforce electrical and mechatronic engineering education. Therefore, engineers can easily access MATLAB, and they already have the basic programming skills to use the given Simulink models and to write computer programs when required for selecting an induction motor for an application.

2. Mathematical Model
2.1. Basic Steady State Equivalent Circuit with Balanced Supply Voltages [1 – 5]

The performance of the three phase IM with a cage rotor can be analyzed with the equivalent circuit method at different stages of its operation. The equivalent circuit is drawn on per phase basis, as shown in Figure (1). At standstill, the IM acts like a transformer. The produced traveling field due to three phase stator currents induces emfs in both the stator and rotor windings of frequency ω_1 as E_1 and E_{2s}, respectively. As the motor speeds up, the rotor emf frequency diminished and becomes ω_2, where ($\omega_2 = s \, \omega_1$). Following the same procedure described in reference [5], Figure (2) represents the per phase equivalent circuit of an IM with the rotor circuit reduced to the stator circuit. In Figure (2), there is only one frequency, the stator frequency ω_1, which means that they refer to an equivalent rotor at standstill, but with an additional "virtual" rotor resistance per phase $R_r'(1/s-1)$ dependent on slip (speed).
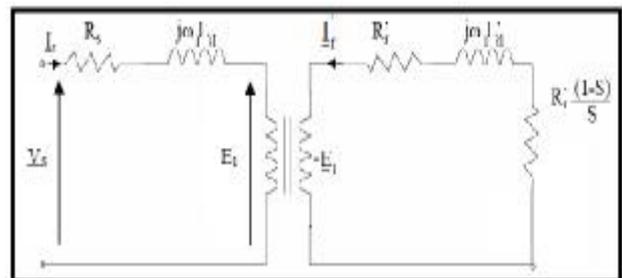

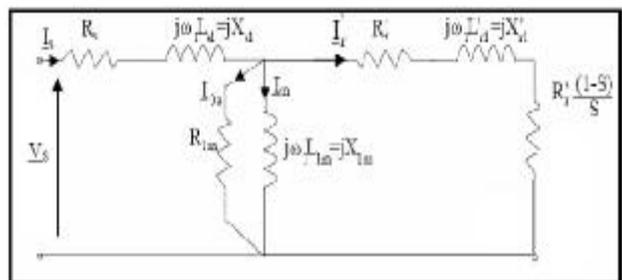**Fig.1. Three Phase IM Equivalent Circuit on Per Phase Basis.**

Fig.2. Three Phase IM Equivalent Circuit on Per Phase Basis Reduced to Stator Circuit.

It is evident that the active power in this virtual resistance is in fact the electromechanical power of the actual motor, where

$$P_m = 3R_r'\left(\frac{1}{s}-1\right)\left(I_r'\right)^2 \qquad \text{(watts)} \qquad \text{...(1)}$$

Hence, the electromagnetic torque (power) which crosses the air gap from stator to rotor may be obtained, as

$$T_e = \frac{3R'_r \left(I'_r\right)^2}{s.w_1} \quad \text{(Synchronous watts)} \quad \dots (2)$$

A definition for the slip is introduced by equation (3) as;

$$s = \frac{3R'_r \left(I'_r\right)^2}{T_e.w_1} = \frac{P_{cur}}{P_e} \quad \dots (3)$$

Equation (3) signifies that, for a given electromagnetic power (torque), for a given frequency, the slip is proportional to rotor winding copper losses.

At ideal no – load IM operation, the input (active) power is dissipated into electromagnetic loss, fundamental and harmonics stator core losses, and stator windings and space harmonics rotor core and cage losses. These losses may be combined in a resistance R_{1m} in parallel with a magnetizing leakage reactance X_{1m}, as in Figure (2). R_{1m} may be calculated from the no – load operation of the IM with the required no – load measurements including the reactive input power. Figure (3) shows the per phase equivalent circuit of an IM running at no – load with the rotor circuit omitted as its copper losses are neglected, ($I'_r \approx 0$).
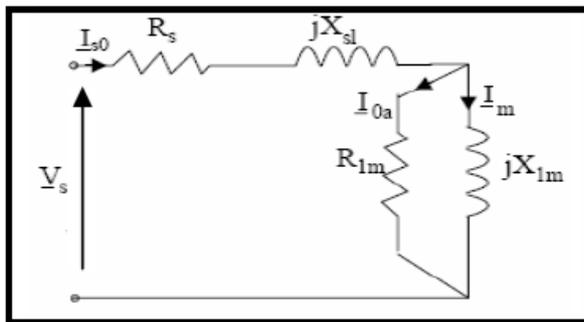

Fig.3. IM Equivalent Circuit on Per Phase Basis Running at No –Load with the Rotor Circuit Omitted.

The relation between the resistance R_{1m} and the magnetizing mutual leakage reactance X_{1m} may be presented as;

$$\frac{R_{1m}}{X_{1m}} = K_0 \quad \dots (4)$$

The constant (K_0) is to be calculated, repeatedly, from the no-load readings at different supply voltage (V_s) and frequency.

2.2. Steady State Characteristics with Unbalanced Supply Voltages

Polyphase IMs are designed to operate most effectively at their nameplate rated voltage. Most motors will operate satisfactorily over (±10 %) voltage variation [6]. Deviations from the nominal motor design voltage can have marked effects on the motor performance. Voltage unbalance can be more detrimental than voltage variation to motor performance and motor life. In general, IMs should be designed (thermally) to stand ±10% voltage variation around the rated value, according to the standards of the NEMA.

Steady state IM performance with unbalanced supply voltages may be treated by the method of symmetrical components [7]. The three-wire supply voltages $\underline{V}_a$, $\underline{V}_b$ and $\underline{V}_c$ are decomposed into zero sequence, forward (+ve) sequence and backward (-ve) sequence components. This can be written in matrix form as;

$$\begin{bmatrix} \underline{V}_0 \\ \underline{V}_+ \\ \underline{V}_- \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \underline{V}_a \\ \underline{V}_b \\ \underline{V}_c \end{bmatrix} \quad \dots (5)$$

With the constant (a) given as

$$a = 1\angle 120^0 = e^{j\frac{2p}{3}} \quad \dots (6)$$

A similar transformation is obtained for each phase current, and is given as

$$\begin{bmatrix} \underline{I}_0 \\ \underline{I}_+ \\ \underline{I}_- \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \end{bmatrix} \quad \dots (7)$$

Thus, beginning with forcing the voltages V_{a0}, V_{b0}, and V_{c0} to have equal magnitude and phase, the zero sequence component of each phase voltage are all defined by a single magnitude and a single phase angle, V_0. Secondly, by forcing the voltages V_{a+}, V_{b+}, and V_{c+} to form a balanced three phase set with forward (+ve) phase sequence. This set of balanced voltages is responsible for producing the forward traveling field in the IM. Finally, forcing the voltages V_{a-}, V_{b-}, and V_{c-} to form a balanced three phase set with backward (-ve) phase sequence. Similar sets

can be obtained for the current (stator or rotor current).

It is worth mentioning that the zero sequence voltage component has almost negligible loss effect on the motor steady state performance. This is due to the fact that its current magnitude is very small in comparison with that of the positive sequence component, $I_0 \approx 0$.

The unbalanced supply voltages may now be represented in terms of their symmetrical components, with $V_f = V_+$ and $V_b = V_-$, as

$$\left. \begin{array}{l} \underline{V}_a = \underline{V}_{a0} + \underline{V}_{af} + \underline{V}_{ab} \\ \underline{V}_b = \underline{V}_{b0} + \underline{V}_{bf} + \underline{V}_{bb} \\ \underline{V}_c = \underline{V}_{c0} + \underline{V}_{cf} + \underline{V}_{cb} \end{array} \right\} \quad \dots (8)$$

Thus, applying equation (5) to obtain the forward and backward voltage components of phase (a), as

$$\left. \begin{array}{l} \underline{V}_{af} = \dfrac{1}{3}\left(\underline{V}_a + a\underline{V}_b + a^2\underline{V}_c \right) \\ \underline{V}_{ab} = \dfrac{1}{3}\left(\underline{V}_a + a^2\underline{V}_b + a\underline{V}_c \right) \end{array} \right\} \quad \dots (9)$$

Noting that phases (b & c) forward and backwards voltage components are obtained as:

$$\left. \begin{array}{l} \underline{V}_{bf} = a^2\underline{V}_{af}; \underline{V}_{bb} = a\underline{V}_{ab} \\ \underline{V}_{cf} = a\underline{V}_{af}; \underline{V}_{cb} = a^2\underline{V}_{ab} \end{array} \right\} \quad \dots (10)$$

As in single phase IM, the slip for the forward component is ($s_f = s$), while for the backward component the slip is ($s_b = 2 - s$). Now, according to equation (9), we have two per phase equivalent circuits with the first one for the forward (+ve) sequence voltage component and the second for the backward (-ve) sequence voltage component, as shown in Figures (4 & 5) respectively.
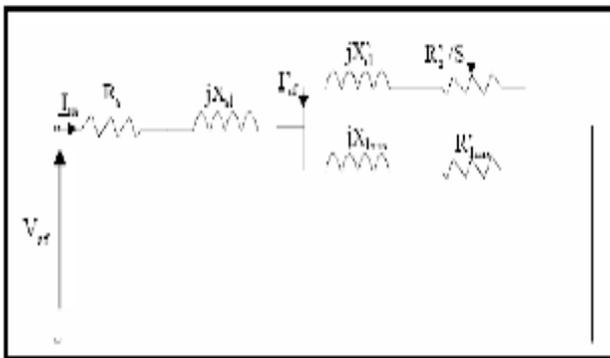

Fig.4. IM Per Phase Equivalent Circuit Supplied by Forward Sequence Voltage Component.
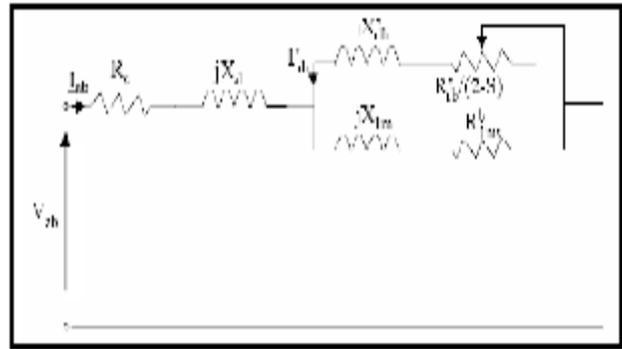

Fig.5. IM Per Phase Equivalent Circuit Supplied by Forward Sequence Voltage Component.

The torque expression contains two components, and is given as;

$$T_e = \frac{3}{w_1}\left(\frac{R_r'\left(I_{rf}' \right)^2}{s} - \frac{R_r'\left(I_{rb}' \right)^2}{2-s} \right) \text{ (N.m)} \quad \dots (11)$$

Due to the presence of the backward torque, the resultant torque will have an oscillating steady state value with a frequency of approximately twice the supply frequency. This, in turns, will cause a vibration in the IM operation [15]. As a consequence, the IM exhibits unscheduled service and maintenance time, especially for its bearings.

The motor percentage efficiency (%η) in terms of power flow, for balanced supply voltages, is given as:

$$\%\eta = \frac{\text{shaft power}}{\text{input electrical power}}$$
$$= \frac{T_m \cdot \omega}{3 \cdot V_{ph} \cdot I_{ph} \cdot Pf} \times 100\% \quad \dots (12)$$

In case of unbalanced supply voltages, and with the presence of the backward (braking) torque, the motor efficiency can be obtained by making use of equations (11&12), as;

$$\%\eta = \frac{T_e(1-s)\omega_1}{3 \cdot \text{Re}\left[\underline{V}_{af}\underline{I}_{af}^* + \underline{V}_{ab}\underline{I}_{ab}^* \right]} \times 100\% \quad \dots (13)$$

$\underline{I}_{af}$ and $\underline{I}_{ab}$ are obtained using the equivalent circuits shown in Figures (4 & 5). Also, they can be obtained by making use of (7) with the stator current calculated from the basic equivalent circuit with three different unbalanced phase voltages.

For calculations with a reference base for the unbalanced supply voltages, the percentage

voltage unbalance index (%V_{unb}) is introduced. This index may be defined as:

$$\% \, V_{unb} = \frac{DV_{max}}{V_{ave}} \times 100\% \qquad \ldots(14)$$

Where:

$$DV_{max} = V_{max} - V_{min}$$

and:

$$V_{ave} = \frac{(V_a + V_b + V_c)}{3}$$

3. MATLAB/Simulink Models
3.1. IM Parameters Data and Simulation Model Implementation

The IM parameters data are listed in Table 1. all parameters are referred (reduced) to the stator circuit. These data were used in both theoretical and simulation calculations. The three phase IM is implemented using the induction machine block in the machine library of the SPS. The electrical inputs of the induction machine are the three electrical connections of the stator (*terminals A-B-C*), while the electrical outputs (*terminals a-b-c*) are the three electrical connections of the rotor. The rotor terminals disappear in cage rotor type selection. The input block (*terminal Tm*) is the mechanical load torque at the machine's shaft.

Table 1,
IM Parameters used in the Simulink Model [8].

Present Model: 5.4 HP, 400 V, 50 Hz, 1430 rpm		
Parameter	Symbol	Type/ Value
Rotor type	---	Squirrel cage
Stator resistance, Ω/ph	R_s	1.405
Stator leakage inductance, H/ph	L_{s1}	0.005839
Rotor resistance referred to stator, Ω/ph	$R_r{'}$	1.395
Rotor leakage inductance referred to stator, H/ph	$L_{r1}{'}$	0.005839
Magnetizing mutual inductance, H	L_{1m}	0.1722
Pole pairs	P_p	2
Combined machine and load inertia coefficient, Kg.m^2	J	0.0131
Viscous friction coefficient, N.m×s)	F	0.002985

The output terminal of the induction motor block (*terminal m*) allows for the measurement of several variables, such as speed and electrical torque. Other different parameters of the IM are specified using the induction machine-block dialog box. The supply voltage is implemented using the AC voltage source block. The parameters of each phase voltage (amplitude, phase angle and frequency) can be varied within their dialog boxes. All other circuit measuring and display units with the in between blocks are drawn from the different branches of the SPS toolboxes.

3.2. No-Load Simulation Model

Figure (6) depicts the SPS/Simulink implementation for the three phase IM steady state no – load operation with nominal (rated) balanced supply voltages and a nominal frequency of 50 Hz. The purpose of this run is to calculate the resistance R_{1m} which its value will be used in theoretical calculations. The calculated value of this resistance is found to be (4126 Ω). Since the value is too high in comparison with X_{1m}, R_{1m} value may be neglected in performing the theoretical calculations.

3.3. IM Operation Supplied by Unbalanced Supply Voltages Simulation Model

The power grid supply voltages that supply an industrial region are measured and recorded. The phase voltages of the power supply at AL-Zaffarania industrial territory in Baghdad are listed in Table 2, with the corresponding date and time. According to these readings, the simulation results have been obtained and compared with theoretical ones.

Figure (7) depicts the Simulink/SPS implementation for the three phase IM steady state operation with unbalanced supply voltages and with a nominal frequency of 50Hz.

Table 2,
Three Phase Supply Voltage Readings at al-Zaffarania Industrial Region.

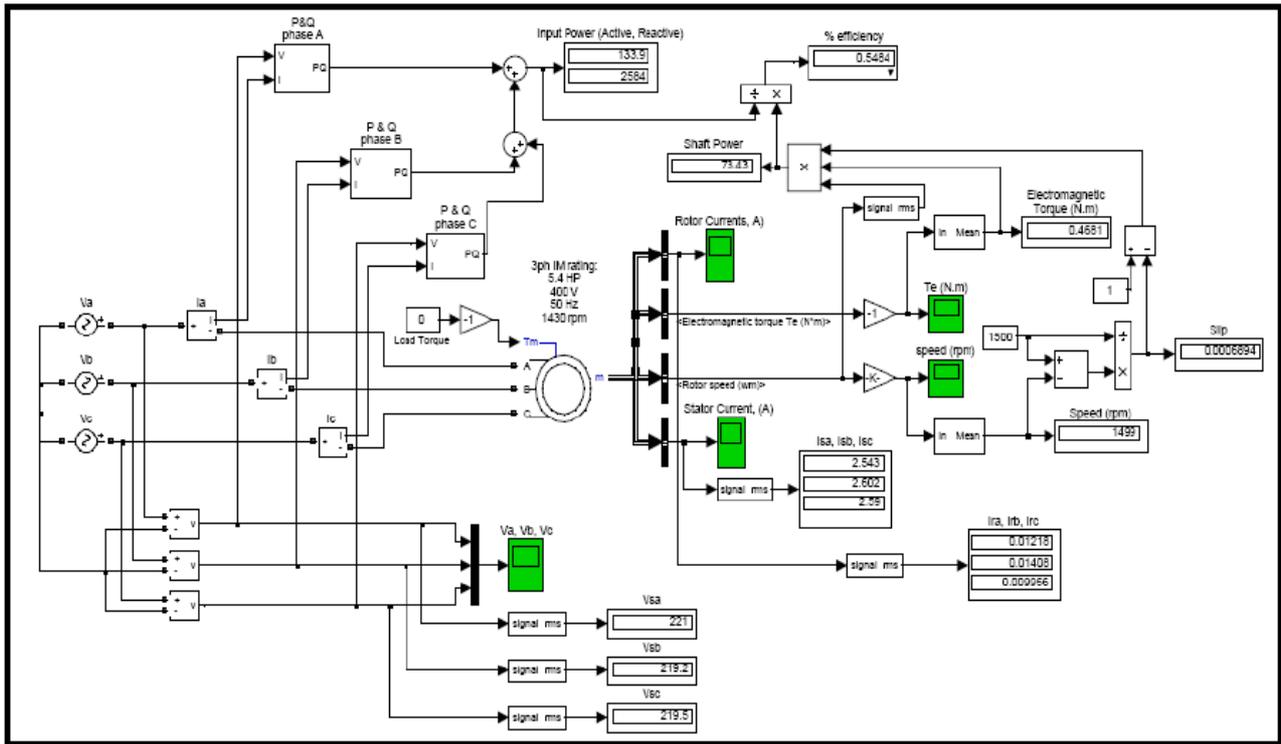| Time	Date	V_B (r.m.s value), V	V_B (r.m.s value), V	V_C (r.m.s value), V
10:30 am	8/7/2010	188.5	196	202
11:40 am	5/8/2010	185	195.7	198.2
12:50 pm	19/1/2011	204	207	218

Fig.6. IM No-Load Steady State Operation with Balanced Supply Voltages and Nominal Frequency.
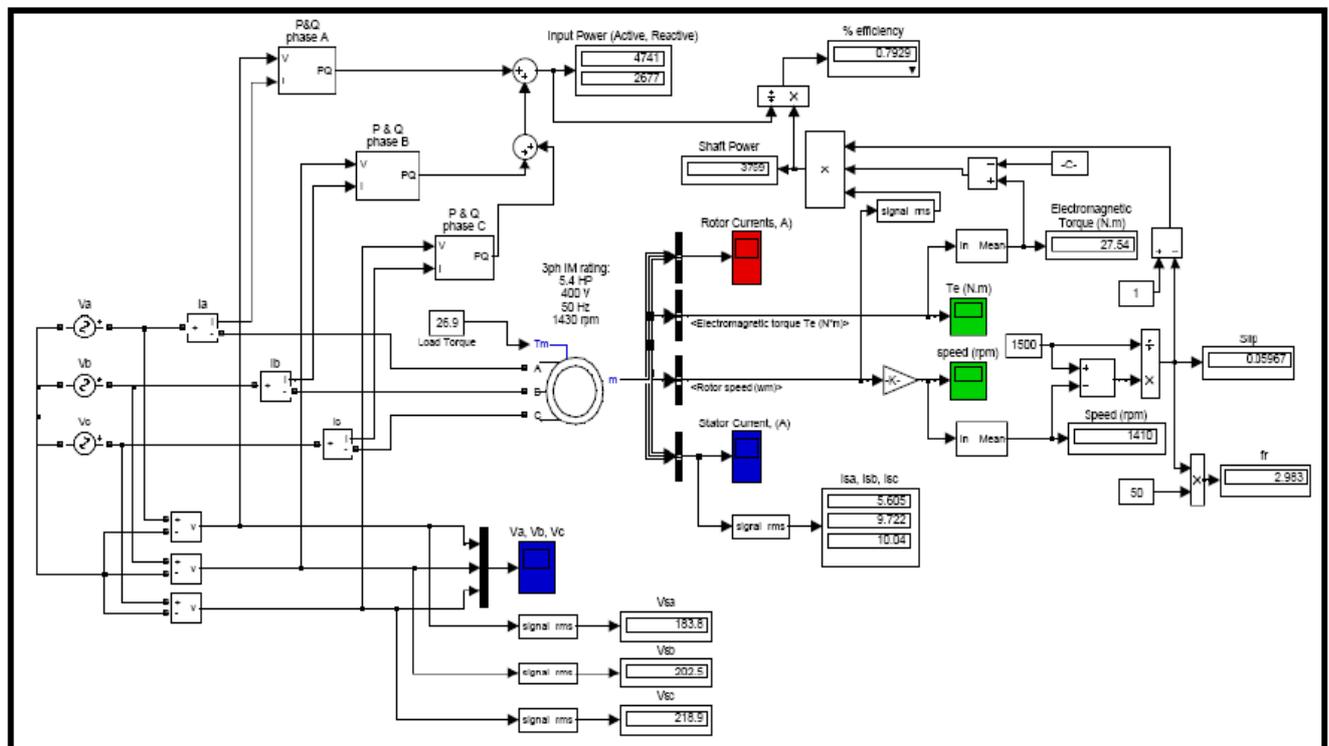

Fig.7. IM Simulation Model Steady State Performance Results with Unbalanced Supply Voltages & Full Load Condition.

4. Results

The equivalent circuit method described in section (2, section 2.2) is used to obtain the theoretical calculations, with the IM data listed in Table 1. Also, with the motor assumed to operate with full load condition, the simulation was carried out, and results were obtained.

For comparison purposes, Table 3 shows the assumed unbalanced supply voltages at nominal frequency with the results obtained using theoretical calculations. Their corresponding values obtained from the IM simulation model are listed, too. The maximum percentage deviation between the results is with a maximum amount of 2.05 %, which gives a good agreement for predicting the steady state IM characteristics with both methods.

Regarding the IM efficiency, the theoretical results are higher than those obtained with the simulation. This is due to the fact that in theoretical calculations the fundamental core losses are neglected (R_{1m} is too high) with the mechanical losses, whereas these losses are represented in simulation model by the viscous friction coefficient.

Figures (8 & 9) show, respectively, the simulink results of the variation of both the electromagnetic torque and speed with time. From the figures, it is clear that the unbalanced supply voltages cause the ripple in both the torque and speed waveforms, due to the presence of the backward, (-ve) sequence component, torque.

Table 3,
Theoretical and Simulation Results for the IM Model Under Investigation.

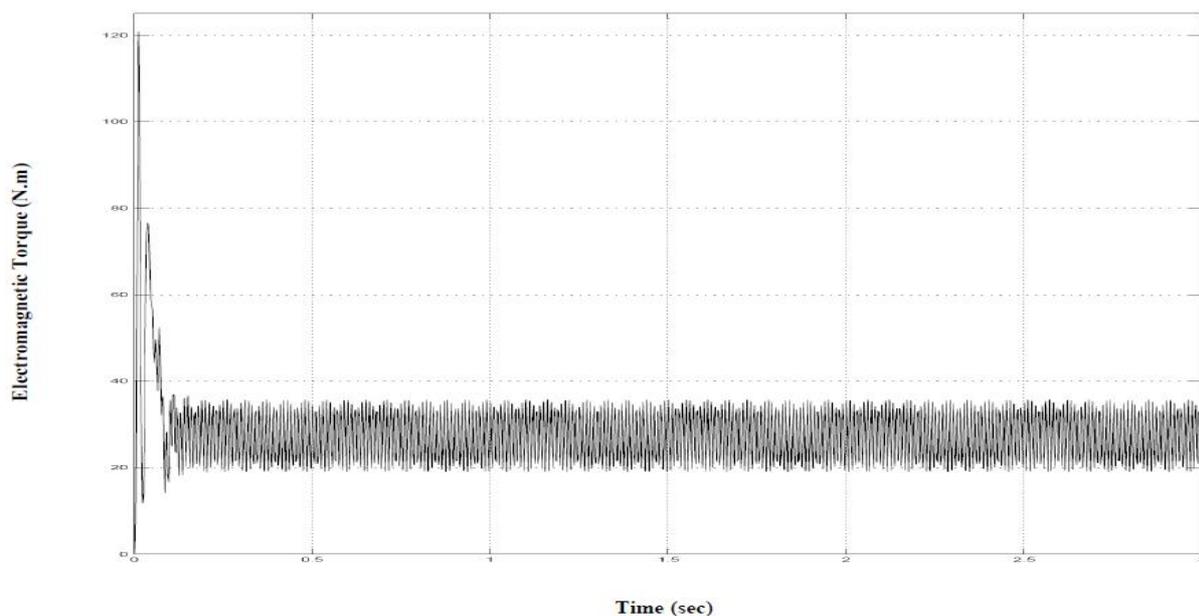| Assumed unbalance supply voltages $V_a = 262\angle 0^0$; $V_b = 283\angle -120^0$; $V_C = 311\angle 120^0$	Theoretical results	Simulation results	% deviation
Slip	0.06	0.05967	0.55
% efficiency	80.01	79.29	0.8999
Electromagnetic torque, N.m	26.517	27.072	2.05
Ripple in speed (ΔN), r.p.m.	---	20	---
Ripple in electromagnetic torque (DT_e)	---	16.72	---

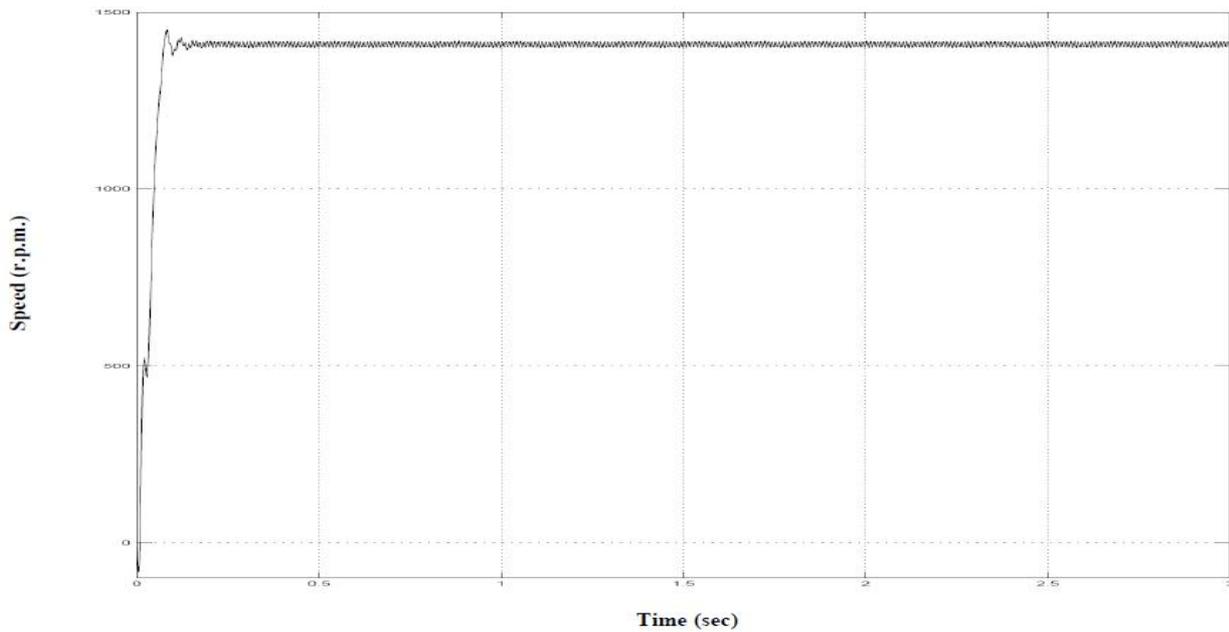**Fig.8. Electromagnetic Torque Variation of IM Running off Unbalanced Supply Voltages.**

Fig.9. Speed Variation of IM Running off Unbalanced Supply Voltages.

Figures (10 & 11) show the per unit efficiency variation (reduction) due to unbalanced voltage that occurs in single – phase and two – phases of the supply voltage, respectively. From the figures, it is clear that the unbalanced supply voltages cause the efficiency to be reduced as the voltage unbalance index increases, due to the presence of the negative sequence losses in stator / rotor circuits with its corresponding backward torque. The theoretical results are well correlated with the simulation results as shown in these figures.

Figures (12 & 13) show the variation of the electromagnetic torque ripple due to unbalanced voltage that occurs in single – phase and two – phases of the supply voltage, respectively. It is clear that the torque ripple increases with the unbalance index which is most effective with single – phase unbalanced voltage rather than the two – phase unbalanced voltage.

Figures (14 & 15) show the variation of the speed due to unbalanced voltage that occurs in single – phase and two – phases of the supply voltage, respectively. Figures (16 & 17) show the variation of the speed ripple due to unbalanced voltage that occurs in single – phase and two – phases of the supply voltage, respectively.

Although the effect of single – phase unbalance is dominant on the speed ripple, the motor speed is greatly affected by the two – phase unbalance in comparison with single-phase unbalance.
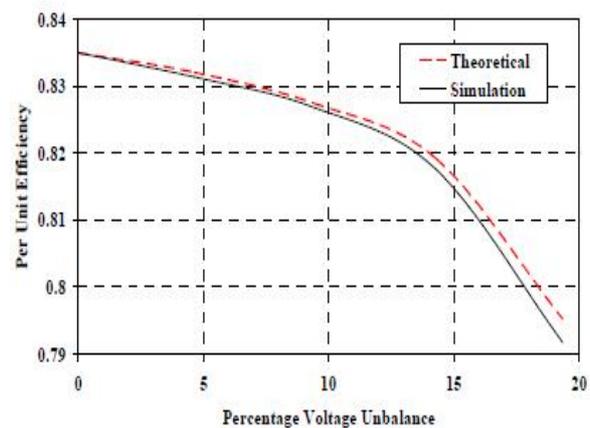

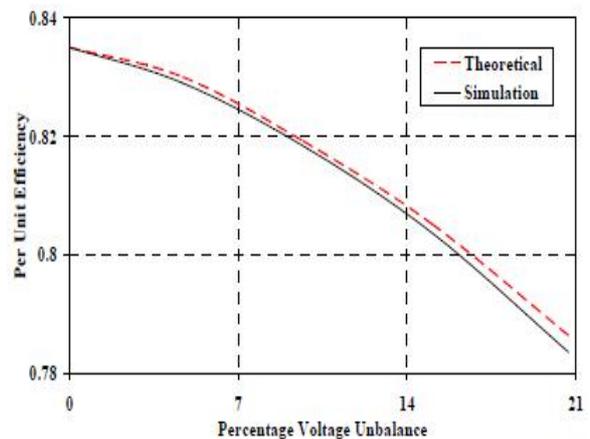**Fig.10. Per Unit Efficiency Variation with 1– Phase Unbalanced Voltage.**

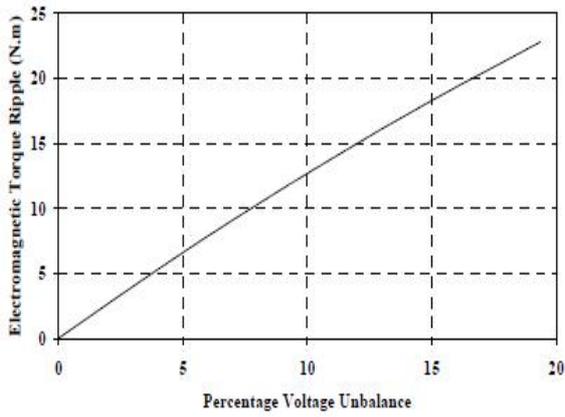**Fig.11. Per Unit Efficiency Variation with 2– Phase Unbalanced Voltages.**

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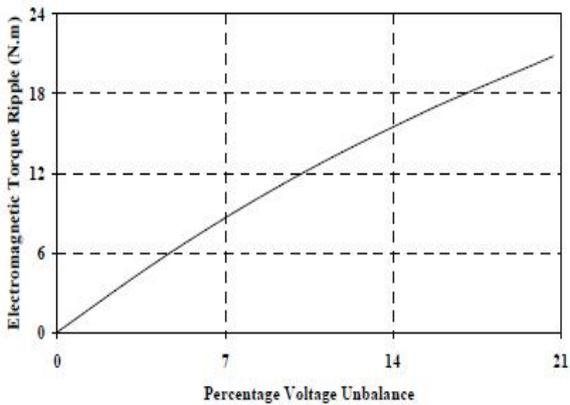**Fig.12. Electromagnetic Torque Ripple Variation with 1– Phase Unbalanced Voltage.**

Fig.13. Electromagnetic Torque Variation with 2– Phase Unbalanced Voltages.
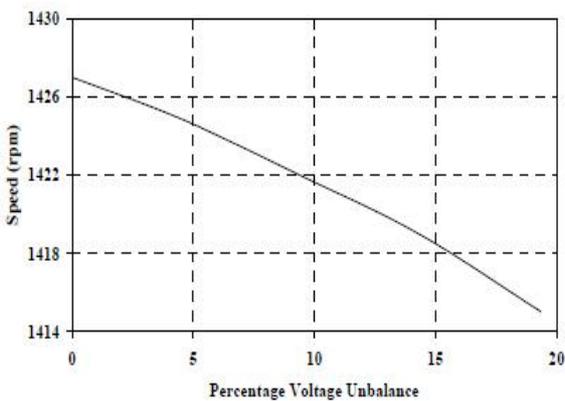
Fig.14. Speed Variation with 1– Phase Unbalanced Voltage.

This can be attributed to the fact that the backward rotor current component and its corresponding torque produced by two-phase unbalance have less frequency, and hence long time duration, than that caused by single-phase unbalance. As a consequence, the resulting torque and its corresponding ripple will be less affected

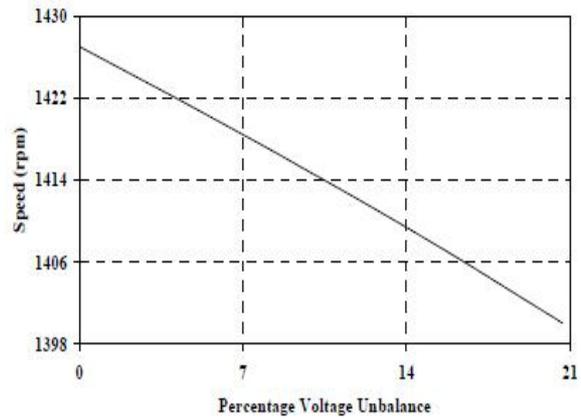by two-phase unbalance, as clearly shown in Figures (12 & 13).

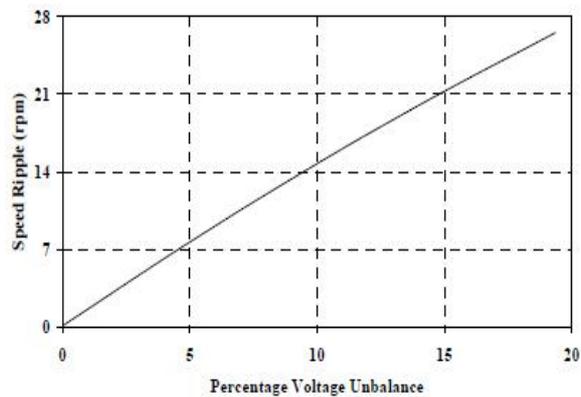**Fig. 15. (Speed variation with 2– phase unbalanced voltages).**

Fig. 16. (Speed Ripple variation with 1– phase unbalanced voltage).
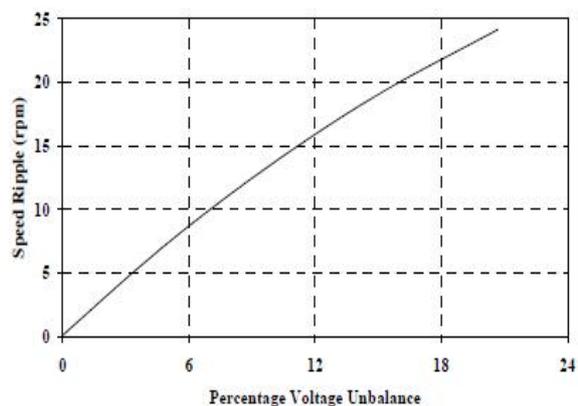
Fig. 17. (Speed Ripple variation with 2– phase unbalanced voltages).

Figures (18 & 19) show the steady state stator phase currents variation with the unbalanced voltage that occurs in single – phase and two –

phases of the supply voltage, respectively. With single – phase unbalanced voltage, the phase that lags the lowest phase has to withstand the current unbalances and supplies the most current for both the negative and positive sequences. This is clear in Figure (18) with phase (b) current. With two – phase voltage unbalance, the leading phase with respect to the phase having the lowest voltage has to withstand the current unbalances. This is clear in Figure (19) with phase (c) current.
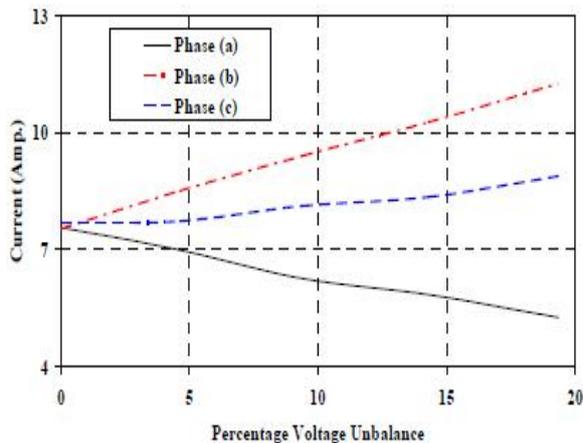

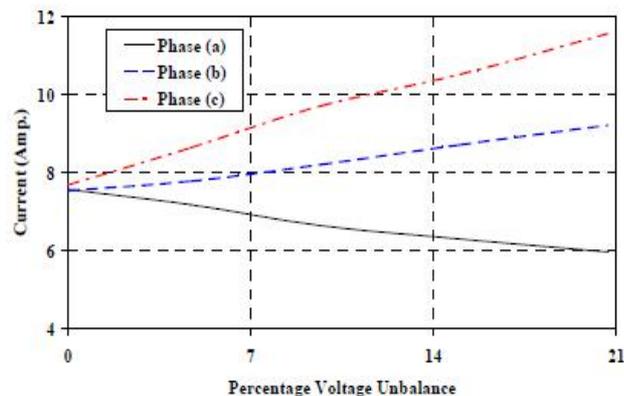**Fig.18. Steady State Stator Phase Currents Variations with 1– Phase Unbalanced Voltage.**

Fig.19. Steady State Stator Phase Currents Variations with 2– Phase Unbalanced Voltages.

If the supply phase voltages and currents are measured, this is a good indication for knowing the voltage sequence and the unbalance type. For both unbalances, as a phase current is increased, an extra heat will be generated in both the stator and the rotor of the IM. In addition, the large unbalance of the stator currents will result in non-uniform temperatures in the motor windings, and an overall motor heat rise.

5. Conclusions

Three phase voltages supplied to an important industrial region in Baghdad-Iraq have been measured and tabulated at different times and dates. The voltages measuring dates and times are chosen as the power grid is subjected to heavy loads. With our poor distribution system, it is found that the absence of unbalanced supply voltages is almost impossible. This is due to many reasons, with uneven distribution of single – phase loads on the three phase power grid system as an important reason.

In this work, the effect of the unbalanced supply voltage on the performance of a conventional three phase induction motor has been introduced. The analysis of $3 - \Phi$, 5 HP, cage rotor IM running off unbalanced supply voltages has been presented. Modeling of the IM using MATLAB/Simulink SPS tools has been introduced. The effect of unbalanced supply voltages on the IM steady state performance has been investigated. Both theoretical and Simulink model results correlate well, with a maximum deviation of 2.05%.

The reported results clarify that unbalanced voltages cause appreciable ripple in both the torque and speed of the induction motor. Also, reduction in motor speed and efficiency results as the voltage unbalance index increases. Considering the most important IM steady state performance indices that are ripple free torque speed characteristics, and the high efficiency with full load condition, the presence of the negative sequence voltage component destroys, directly, these indices. Also, both single – phase and two – phase unbalanced voltages result in higher stator currents. As a consequence, unbalanced heating of stator windings results, an overall rise in motor temperature and production of unbalanced forces on the motor bearings occur. This, in turns, directly affects the motor life time with the requirements of unscheduled motor maintenance. This would appear to be of a serious concern, especially with the motors that operate with small or no service margins.

List of Principal Symbols

s	Slip
s_f	Forward slip
s_b	Backward slip
E_1	Stator emf induced, V/phase

E_{2s}	Rotor emf induced, V/phase
I_r	Rotor phase current, A
I_{rb}'	Backward component rotor phase current referred to stator, A
I_{rf}'	Forward component rotor phase current referred to stator, A
I_s	Stator phase current, A
L_r	Per phase rotor leakage inductance, H
L_s	Per phase stator leakage inductance, H
P_{cur}	Rotor winding copper losses, watts
P_{elm}	Rotor electromagnetic power, watts
P_m	Electromechanical power, watts
P_p	Air gap traveling field spatial pole pairs
R_r	Per phase rotor resistance, Ω
R_r'	Per phase rotor resistance, Ω
R_s	Per phase stator resistance, Ω
R_{1m}	Resistance representing the core loss, Ω
T_e	Electromagnetic torque, N.m
$\underline{V}_0, \underline{V}_+, \underline{V}_-$	Zero, positive and negative voltage components, V
$\underline{V}_a, \underline{V}_b, \underline{V}_c$	Three phase supply phasor voltages, V
$\underline{V}_s$	Per phase stator applied voltage phasor, V
X_{1m}	Magnetizing leakage reactance, Ω

Greek Letters

η	Efficiency
ω	equal to $2\pi f$

6. References

[1] V. K. Mehta and Rohit Mehta, Principles of Electrical Machines, 2nd edition, S. Chand & Company LTD., ND, 2009.

[2] M. N. Bandyopadhyay, Electrical Machines: Theory and Practice, Prentice-Hall of India, N. Delhi, 2007.

[3] Stephen J. Chapman, Electric Machinery Fundamentals, 4th edition, McGraw-Hill, Inc., 2004.

[4] M. Barnes, Variable Speed Drives and Power Electronics, Newnes, 1st edition, GB, 2003.

[5] I. Boldea and S. A. Nasar, The Induction Machine Handbook, CRC Press LLC, 1st edition, 2002.

[6] NEMA Standards Publication No. MG 1-1993, Motors and Generators, Published by the National Electrical Manufacturer's Association.

[7] L. L. Grigsby, Electric Power Engineering Handbook, CRC Press LLC, 2nd edition, 2006.

[8] SIMULINK, Model-based and system-based design, using Simulink, MathWorks Inc., Natick, MA, 2000.

[9] SimPowerSystems for use with Simulink, users guide, MathWorks Inc., Natick, MA, 2002.

[10] M. H. Nehrir, F. Fatehi, and V. Gerez, Computer modeling for enhancing instruction of electric machinery, IEEE Trans Educ., Vol. 38 (1995), 166 – 170.

[11] W. M. Daniels and A. R. Shaffer, Re-inventing the electrical machines curriculum, IEEE Trans Educ., Vol. 41 (1998), 92 – 100.

[12] K. L. Shi, T. F. Chan, Y. K. Wong, and S. L. Ho, Modeling and simulation of the three-phase induction motor using Simulink, IJEEE Vol. 36 (1999), 163 – 172.

[13] S. Ayasun and C. O. Nwankpa, Transformer tests Using MATLAB/Simulink their integration into undergraduate electric machinery courses, Com. App. Eng. Educ., Vol. 14 (2006), 142 – 150.

[14] S. Ayasun and C. O. Nwankpa, Induction motor test using Matlab/Simulink and their integration into undergraduate electric machinery courses, IEEE Tr. Educ., Vol. 48 (2005), 37 – 46.

[15] J. D. Kueck, D. A. Casada and P. J. Otaduy, A Comparison of Two Energy Efficient Motors, IEEE Trans. EC, Vol. 13, No. 2, June 1998, 140 – 147.

التحقق من خواص الحالة المستقرة للمحرك الحثي التقليدي ثلاثي الأطوار عندما يغذى من مصدر غير متساوي (متوازن) الفولتيات

آصلان صباح الدين جلال عبدي
قسم هندسة الميكاترونكس/ كلية الهندسة الخوارزمي/ جامعة بغداد
البريد الالكتروني: aslannabdi@yahoo.com; aslan.kecbu@uobaghdad.edu.iq

الخلاصة

إنّ هدف هذا العمل هو دراسة خواص المحرك الحثي التقليدي ثلاثي الأطوار عندما يجهز من المصدر مع عدم تساوي القيم العظمى لفولتيات المصدر. مع هذا المجهز المضطرب، تم إستخدام طريقة تحليل الدائرة المكافئة للطور الواحد ومفهوم المكوّنات المتماثلة لأغراض التحليل النظري.أيضا, تم دراسة خواص الحالة المستقرة للمحرك في حالة الحمل التام بتمثيل المحرك بإستخدام نظام المحاكاة الموجودة في برنامج ال (Matlab). المقارنة بين نتائج منظومة المحاكاة ونتائج التحليل النظري هي الحكم في تأكيد الطريقة النظرية المستخدمة، و تأكيد أنموذج المحاكاة الذي بني لإستقراء خواص المحرك للحالة المستقرة. إنّ إنموذج المحاكاة بني لدعم وتحسين فهم و إستيعاب المهندسين الكهربائيين لأداء المحرك تحت هذا الإضطراب المجهز من المصدر.